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# Socioeconomic Factors Associated with Increasing Street Tree Density and Diversity in Central Indianapolis

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Urban trees provide an abundance of benefits to city residents. Information about the geographic distribution of urban trees is critical to ensure equitable access to these benefits. Street trees are unique among urban trees because they are often managed by municipalities as a public resource, but they are challenging to manage in part because they are spatially dispersed across a city in close proximity to private property. While street tree inventory data sets are costly to generate, they provide important information to understand the spatial distribution of trees in the city and to plan for ongoing street tree management. Here, we utilize two street inventories collected at a 13-year interval to assess patterns and changes in municipal street tree distributions in Center Township, Indianapolis, IN. In the township as a whole, tree density, basal area, and taxonomic diversity increased markedly over time. Spatial autoregressive models were constructed to examine the relationship between socioeconomic characteristics and street tree population dynamics. Concurrent, legacy, and change models revealed significant associations between socioeconomic factors and street tree distributions. Specifically, tree density and taxonomic diversity were positively associated with educational attainment, and increases in tree density over time were negatively associated with the percent of the population that identifies as black or African American. Results suggest that despite overall increases in street trees, persistent inequalities in street tree access should be addressed in central Indianapolis neighborhoods.

## Keywords

urban forestry, urban ecology, street trees, urban geography, socioeconomics, cities, Indianapolis

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# INTRODUCTION

The benefits of urban trees are becoming well understood. Urban trees are frequently used as public amenities that increase greenspace and improve public health (Kuo 2003; Bell et al. 2008). Trees are also considered engineering solutions to mitigate environmental problems such as stormwater runoff (Berland et al. 2017; Kuehler et al. 2017) and energy consumption (Ko 2018). As municipal assets, trees on public property can provide substantial financial, social, and environmental benefits (along with some disservices) (Escobedo et al. 2011; Mullaney et al. 2015). The proximity of urban trees to residents influences how citizens experience these associated benefits (e.g., shade, increased property values, neighborhood aesthetics) and costs (e.g., allergens, pruning needs). Understanding how urban trees - and especially publicly managed trees - are distributed spatially with respect to human population characteristics is important for municipalities to assess the resulting distribution of ecosystem services and disservices (Landry and Chakraborty 2009; Donovan and Mills 2014).

## Tree Distributions and Environmental Inequality

In general, the existing urban forestry literature has emphasized the positive roles of trees in urban social-ecological systems. While research demonstrates that trees provide a variety of benefits, studies have indicated that tree stems and tree canopy are often not distributed equally with respect to race and income (Heynen et al. 2006; Landry and Chakraborty 2009; Danford et al. 2014; Schwarz et al. 2015; Gerrish and Watkins 2018; Watkins and Gerrish 2018). This unequal distribution of urban tree cover has generated concerns about environmental justice with respect to unequal access to environmental amenities. The distribution of urban trees and associated benefits are often analyzed using canopy cover, or the proportion of the land's surface that is occupied by tree canopies when viewed from above. For example, multi-city analyses have demonstrated consistent associations between tree canopy cover and income (Schwarz et al. 2015; Gerrish and Watkins 2018), and urban vegetation cover has been linked to socioeconomic class and behavior, such as the consumption of environmentally related goods and services (Grove et al. 2006; Grove et al. 2014).

Studies have tracked changes in urban canopy cover over time in relation to land use changes (Berland 2012), policies (Landry and Pu 2010), and socioeconomic dynamics (Chuang et al. 2017; Locke et al. 2017). But most urban tree canopy studies have stopped short of separating publicly vs. privately managed trees. Indeed, an explicit focus on street trees, or trees located in public rights-of-way along streets, permits analysis of trees under direct municipal management because the local government is legally responsible for street tree management in the majority of US municipalities (Hauer and Peterson 2016). Street tree abundances have been found to vary by both management practices and community racial composition (Landry and Chakraborty 2009; Berland and Hopton 2014). Furthermore, differences in species preferences or in species suitability to varying planting sites can lead to different planting choices, which may drive heterogeneous vulnerability to pests and pathogens at fine spatial scales within an urban area (Berland and Elliott 2014). Studies of street tree distribution suggest a similar influence of socioeconomic factors as to urban tree canopy; however, these studies are comparatively few, presumably because street tree data are more costly to generate than canopy cover data. Yet, because municipalities have greater control over street tree populations than urban tree canopy writ large, a better understanding of geographic patterns in street tree abundance and taxonomic diversity could lead to improved management practices because street tree management is central to the work of municipal arborists (Hauer and Peterson 2016).

## Legacies in Urban Forests

Past socioeconomic factors and urban forest management decisions influence current urban forest patterns (Roman et al. 2018). Cities and even neighborhoods can have unique and contrasting legacy effects. Neighborhoods with older homes had greater species diversity in Los Angeles, CA (Clarke et al. 2013) and greater species richness in Salt Lake County, UT (Avolio et al. 2018), while decreased diversity was associated with neighborhood age in Phoenix, AZ (Hope et al., 2008). Interestingly, past socioeconomic characteristics are often better predictors of contemporary land cover than current characteristics (Luck et al. 2009; Boone et al. 2010; Cook et al. 2012). In addition, planting and maintenance choices made by local actors -including municipalities, nonprofits, and residents - often differ in both process and goals (Conway and Vander Vecht 2015). These choices have the potential to alter urban forest trajectories. This is noteworthy given that a disproportionately small number of studies examine the influence of past socioeconomic and municipal management factors (Cook et al. 2012). A better understanding of street tree population changes relative to socioeconomic changes can help monitor and address inequalities in municipal street tree distributions.

## Street Tree Population Dynamics over Time

Tree inventory data provide important information about individual trees that is not typically captured by canopy cover. For example, inventory data contains the location of individual trees, including small individuals that may not be detected in a canopy cover classification but which may grow to a large size in the future. Inventory data sets contain taxonomic identifications that are exceptionally difficult to classify using remotely sensed imagery. Inventory data often contain tree measurements to quantify size, and tree condition ratings to identify maintenance needs. Street tree inventory data may be preferable to canopy cover data when studying municipally managed street trees because tree canopies emanating from private yards into the public right-of-way along streets are difficult to distinguish from canopy provided by publicly maintained trees in the right-of-way.

Studies using street tree inventory data have been less common than tree canopy studies, and there are even fewer analyses tracking changes in street tree inventory data over time (but see Dawson and Khawaja 1985; Roman 2013). Due to the stressful nature of the urban streetscape, much of the literature in the area has been focused on demography (e.g., Roman et al. 2016; van Doorn and McPherson 2018), especially mortality rates of street trees (Koeser et al. 2013; Vogt et al. 2015). While tree mortality is clearly important, meta-analysis has indicated that street tree life expectancy may be underestimated (Roman and Scatena 2011). Much less is known about how other street tree population dynamics including tree density and diversity change over time, and there is virtually no research regarding how socioeconomic factors relate to such changes.

In light of the knowledge gaps regarding how street tree populations change over time (particularly in terms of tree counts, sizes, and taxonomic diversity), the objectives of this study were to assess the concurrent socioeconomic and land use relationships to population dynamics of a street tree population in the past and present. We did this using two street tree inventories for Center Township, Indianapolis, IN from 2002 and 2015, respectively. We also examined the legacy effect of socioeconomic and land use characteristics over a 13 year period, and we analyzed changes observed in the street tree population over time. Our hypotheses are as follows:

(1) Socioeconomic inequalities in central Indianapolis influence both the distribution and population characteristics of publicly owned street trees. A higher density and diversity of trees will signal higher investment and intentionality in tree planting in areas with residents that tend to be wealthier, White, more highly educated, and home owners.

(2) Socioeconomic patterns in the past have a legacy effect on the current distribution of street trees in central Indianapolis, such that past socioeconomic variables can predict current street tree characteristics.

(3) Current socioeconomic characteristics can explain changes in street tree characteristics over time. This could be a combined effect of (a) residents who are wealthier and more highly educated, for example, choosing to move to areas with more street trees, and/or (b) those residents exhibiting a demand for street trees once they live in those places.

## METHODS

### Study Area

The location of this study was Center Township of Marion County, Indiana (Figure 1). Marion County is consolidated with the City of Indianapolis as a single governing body. Center Township is 110.6 km$^2$ (42.7 mi$^2$) and includes the downtown area of Indianapolis. The population of Center Township in 2015 was estimated as 146,116 (U.S. Census Bureau 2019). Indianapolis is located within USDA Plant Hardiness Zone 6a (USDA 2012). The city receives an annual average of 107.2 cm of precipitation (US Climate Data 2019). The annual average temperature in Indianapolis is 11.7°C, with average high temperatures ranging from 2.0°C in January to 29.4°C in July (US Climate Data 2019). Emerald ash borer (EAB), a highly destructive invasive pest targeting *Fraxinus* spp., was present in all nine townships of Marion County during the study period. EAB was first detected in Lawrence Township of Marion County in 2006 (Indiana EAB 2019). As of August 2017, about 1,600 ash trees were removed due to EAB, and over 20,000 additional ash trees were expected to be removed by 2021 (Bowman 2017). Thus, only a portion of EAB's impacts were evident in the following data sets.

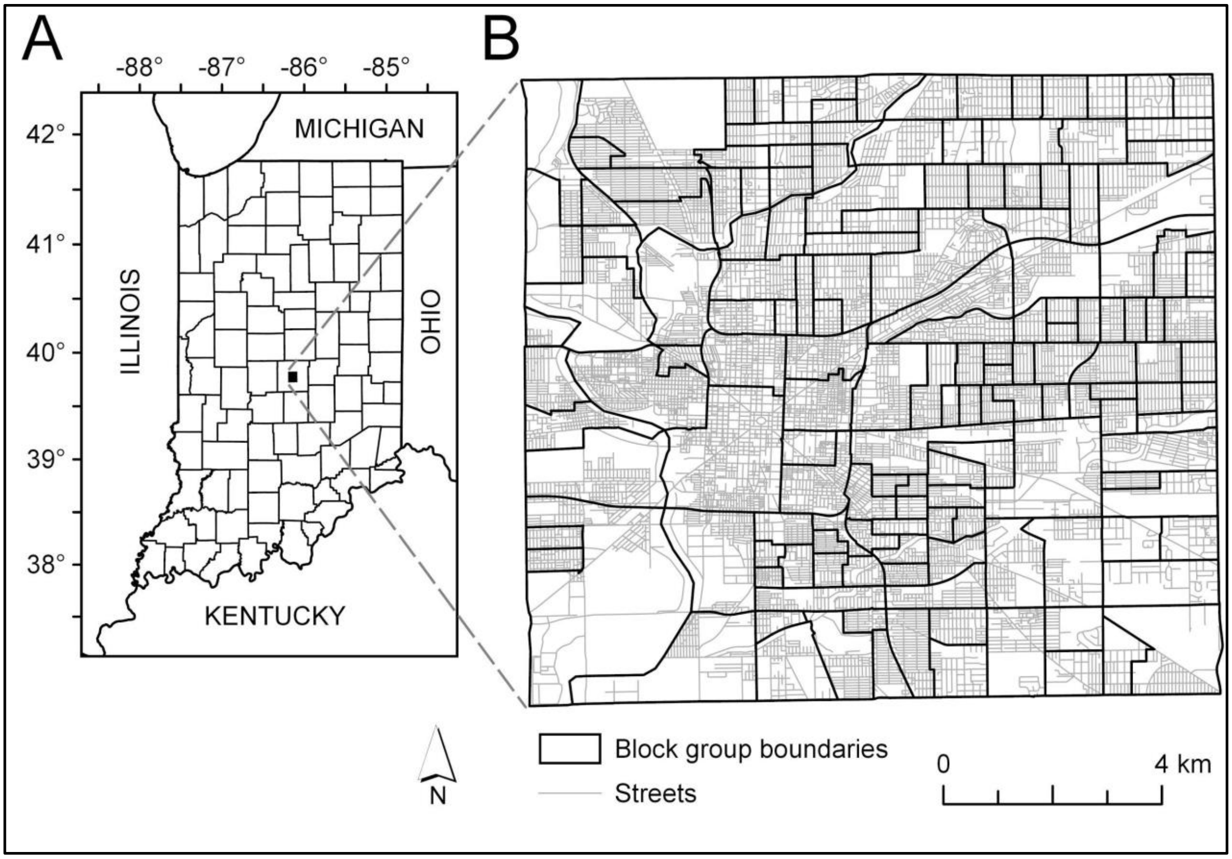


**Figure 1**. (A) The study area is Center Township (black), located in Marion County, Indiana. Indiana county boundaries (black lines) are shown for reference. (B) The Center Township study area contains 154 block groups.

## Urban Forest Management

The management of street trees and other public trees in Center Township is the responsibility of the City of Indianapolis. The City's urban forestry program is jointly funded by the Department of Public Works and the Department of Parks and Recreation. The City's average annual urban forestry expense from 2002-2016 was $2,894,002, which contributed to tree planting projects (street trees and other public trees) and maintenance activities. While the City maintains street trees, residents may apply for permits to plant, prune, or remove street trees. Keep Indianapolis Beautiful (KIB) is a local nonprofit organization which has also been planting trees (including street trees) in Indianapolis since 1976 (KIB 2019). KIB planted over 50,000 total trees from 2006 to 2017 (KIB 2019).

## Street Tree Data

Two data sets were acquired from the City of Indianapolis, consisting of complete street tree inventories in Center Township. The first inventory (Center Township only) was conducted during 2002-2003. The second inventory (citywide) was conducted during 2013-2016. For simplicity, we refer to these inventories as the 2002 and 2015 inventories, respectively, because 97% of trees from the first inventory were recorded in 2002 and 95% of Center Township trees from the second inventory were recorded in 2015. The second inventory included street tree data for all nine townships in Marion County, but only Center Township was used for this study. The inventories were conducted by field crews supplied by a professional contractor. The contractor had quality control procedures in place to ensure high data quality. We were unable to quantify the degree of error in the data sets because we were not provided with quality assessment data generated at the time of the inventories, so we analyzed the data sets under the assumption that the data were accurate. The data sets were provided to us as geographic information systems (GIS) map layers. Prior to analysis, we removed data points that were not living trees (e.g., available planting spaces, stumps). As described below, our analysis focused on three components of the data sets, namely the tree's location, genus, and diameter at breast height (DBH).

Street tree metrics were calculated at the census block group level within Center Township to match the finest resolution of socioeconomic data available from the US Census Bureau (see below). Each tree was associated with its respective block group using a spatial join in ArcMap 10.5 (ESRI 2016).Three metrics were used to represent the street tree population characteristics and dynamics: tree density, basal area, and Simpson's Diversity Index (SDI). A small percentage of trees were recorded as 'unknown' species in both the 2002 (0.3%) and 2015 (0.7%) inventories; these unidentified trees were included in tree density and basal area calculations, but not in SDI calculations. Tree density was calculated as trees per kilometer of right-of-way, and basal area was calculated as $m^2$ per kilometer of right-of-way. Linear distance of right-of-way within block groups was used instead of land area, because trees are planted in a linear fashion along streets (following Berland and Hopton 2014). Basal area was included as a proxy for increased provision of ecosystem services by larger trees (McPherson 2003), because stem diameter is predictive of other tree metrics such as leaf area that drive the provision of many ecosystem services (Semenzato et al. 2011). Basal area was calculated using field measurements of DBH, which was recorded to the nearest 1 inch (2.54 cm). SDI for each block group was calculated at the genus level; we report the inverse Simpson index ($1/D$), which increases with increasing diversity. SDI has been used to compare diversities among street tree populations (Sun 1992). SDI was calculated to the level of genera, rather than species, for multiple reasons. Trees are occasionally misidentified at the species level during data collection, and we presumed that genus misidentification rates would be substantially lower because trees are typically mistaken for other species in the same genus (Ball et al. 2007). Approximately 8% of trees in the 2002 inventory and 12% of trees in the 2015 inventory were only identified to the genus level, so it would be inappropriate to use those trees in species diversity calculations. Also, pests often exploit many species within a genus, and a pest's species preferences are typically not reliably quantified (Sjöman et al. 2014), making genus diversity a relevant metric for urban forestry management.

**Socioeconomic Data**

Socioeconomic data in block groups were gathered from the US Census Bureau (2019). We selected 2000 census data to represent the demographics during the 2002 street tree inventory, and 5-year estimates in 2015 from the American Community Survey for the 2015 inventory. Six socioeconomic variables were compiled at the block group level (Figure 2): median household income, percent Black or African American, percent of adults age 25 and higher with a bachelor's degree or higher, percent owner occupancy, population density, and the density of housing units (per kilometer of right-of-way). These variables were selected because they have been important in helping to understand how urban forest variables relate to socioeconomic conditions and land use (Heynen et al. 2006; Landry and Chakraborty 2009; Lowry et al. 2012; Schwarz et al. 2015). Housing density was calculated using right-of-way length because street trees are only planted in the right-of-way, and using total land area would artificially lower this density calculation in block groups containing large parks, cemeteries, and other land uses with few roads. Right-of-way data and street centerline data were obtained from the City of Indianapolis. To analyze temporal relationships we calculated percent change for street tree response variables. The terms "past" and "present" were used to designate variable values pertaining to time periods during the 2002 and 2015 inventories, respectively. Percent change was calculated as follows:

*(present value - past value)/past value * 100.*

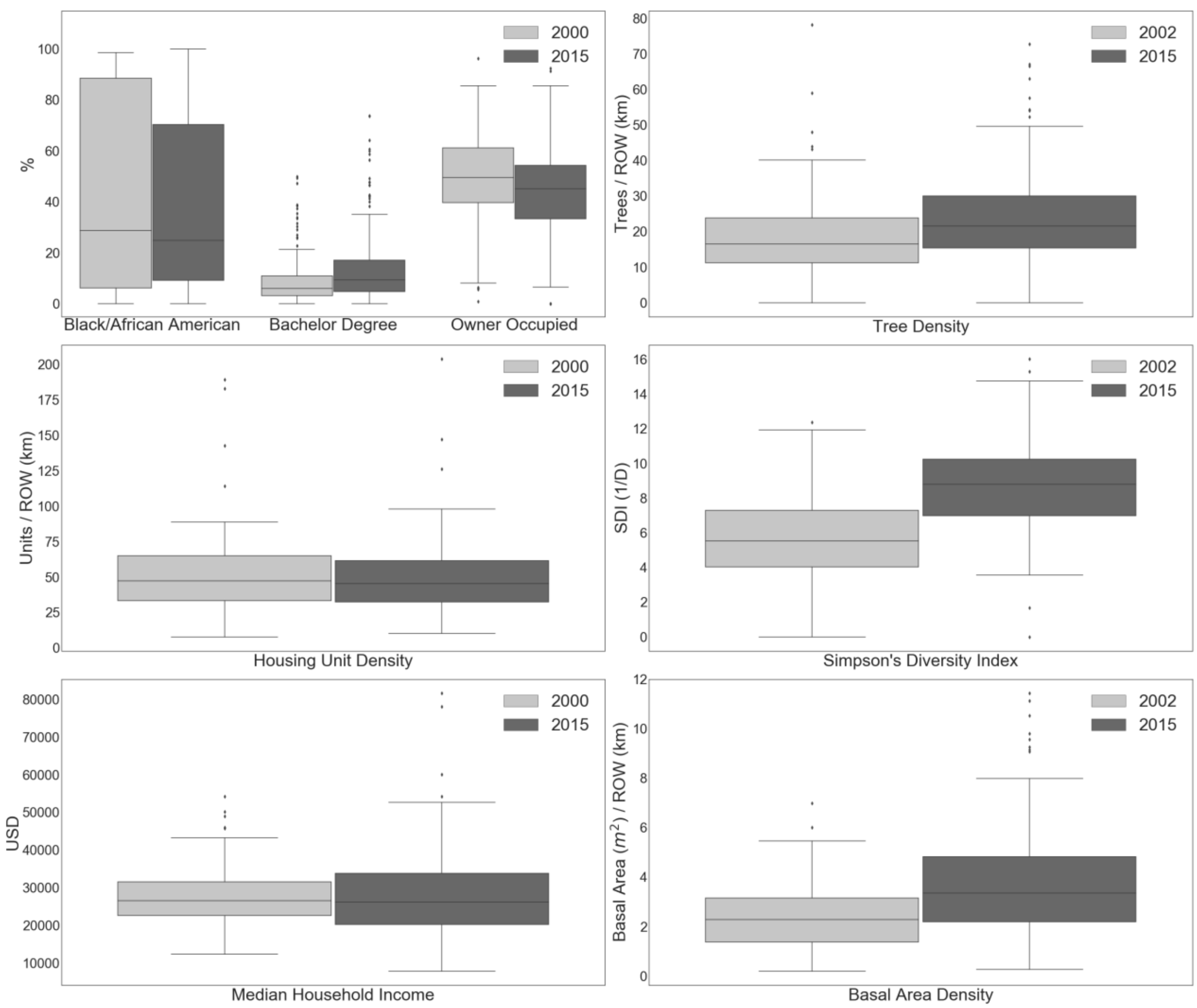


**Figure 2.** Boxplots comparing past and present socioeconomic and street tree characteristics by block group.

## Analysis

We used multivariate linear regression to analyze the relationships among the socioeconomic variables and street tree variables. Three separate models were constructed to analyze different aspects of the relationships between socioeconomic factors and street tree population dynamics: the concurrent model, the short-term legacy model, and the percent change model. In the concurrent model, we used socioeconomic and street tree data to examine the relationships separately for 2002 and 2015. The short-term legacy model used past socioeconomic data and present street tree data to examine legacy effects of past resident characteristics on the current street tree population. The percent change model used current socioeconomic data with percent change of street tree data to determine relationships between changes in the street tree population and contemporary block group characteristics where the changes occurred.

Before performing regression analysis, Spearman's rank-order correlation was used to assess multicollinearity among the explanatory variables. We excluded a variable when excessive multicollinearity was evident; the cutoff for exclusion was a Spearman's rank correlation coefficient with an absolute value of 0.7 or higher (Dormann et al. 2013). Two variables exhibited a correlation higher than the 0.7 threshold: population density and housing unit density. Ultimately, housing unit density was retained as it accounts for both population and land use characteristics.

Ordinary least squares (OLS) regression was used to explain variation in tree density, genus diversity, and basal area. Spatial autoregressive models (SAR) were implemented when OLS regression residuals exhibited significant spatial autocorrelation as assessed using the Moran's *I* statistic (following Landry and Chakraborty 2009), because this indicates a pseudoreplication issue that violates the OLS assumption of independent observations. We implemented spatial lag SAR models with a first order queen's contiguity weight matrix using GeoDa version 1.8 (Anselin et al. 2006). In the regression models, independent variables with a *p*-value less than 0.05 were considered significant.

## RESULTS

Across Center Township, street tree metrics capturing tree density, genus diversity, and basal area all increased over the study time period (Figure 2), and the majority of individual block groups experienced increases in these metrics (Figure 3). Table 1 presents an overview of the two inventories by genus. It shows a substantial increase in the total number of street trees in Center Township, and a reduction in the proportional representation of the three most common genera in 2002 (*Acer, Fraxinus,* and *Malus*) by 2015. The median DBH was 9 inches (23 cm) in both inventories (Table 1). Genera with steady or declining populations from 2002 to 2015 (e.g., *Acer, Fraxinus, Tilia*) saw an increase in the median DBH over time, while the median DBH decreased for genera that increased in number from 2002 to 2015 (e.g., *Quercus, Celtis, Platanus*) (Table 1).

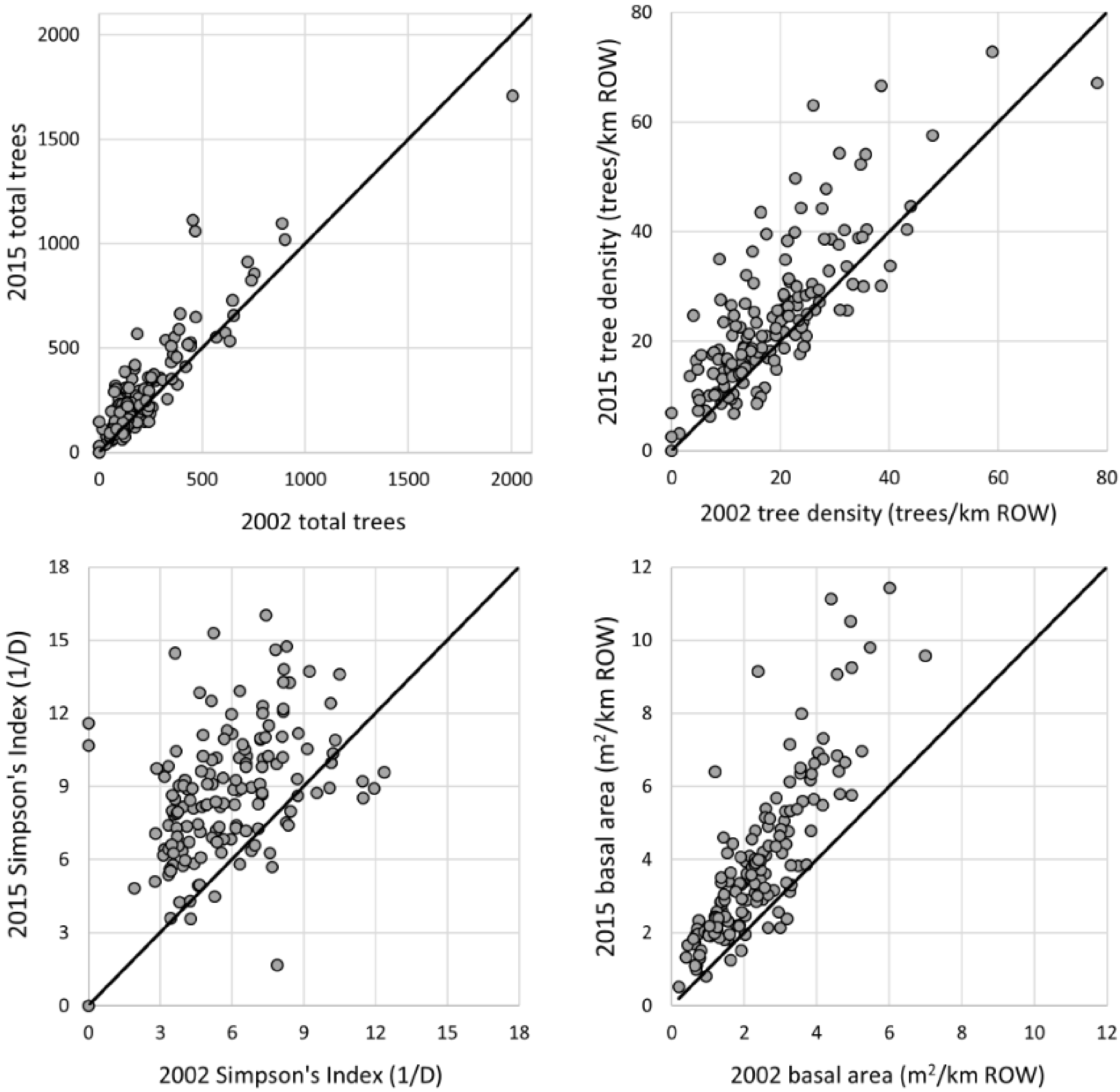


**Figure 3.** Scatterplots comparing street tree characteristics by block group, 2002 vs. 2015. Data points above the black 1-to-1 line indicate block groups for which the metric increased over time, while data points below the 1-to-1 line indicate block groups that experienced a decrease.

**Table 1**. Genus summary for the most common genera in Center Township for the 2002 and 2015 inventories. Med. DBH = median diameter at breast height, measured to the nearest inch

| 2002 | | | | 2015 | | | |
|---|---|---|---|---|---|---|---|
| **Genus** | **Count** | **%** | **Med. DBH** | **Genus** | **Count** | **%** | **Med. DBH** |
| *Acer* | 10,091 | 30.0 | 15 | *Acer* | 9,303 | 21.6 | 15 |
| *Fraxinus* | 3,327 | 9.9 | 7 | *Morus* | 3,361 | 7.8 | 5 |
| *Malus* | 2,938 | 8.7 | 3 | *Ulmus* | 3,142 | 7.3 | 8 |
| *Pyrus* | 1,755 | 5.2 | 4 | *Quercus* | 2,889 | 6.7 | 4 |
| *Ulmus* | 1,726 | 5.1 | 16 | *Fraxinus* | 2,423 | 5.6 | 13 |
| *Gleditsia* | 1,286 | 3.8 | 8 | *Pyrus* | 1,798 | 4.2 | 10 |
| *Quercus* | 1,252 | 3.7 | 16 | *Malus* | 1,771 | 4.1 | 7 |
| *Morus* | 1,109 | 3.3 | 7 | *Celtis* | 1,587 | 3.7 | 10 |
| *Picea* | 1,032 | 3.1 | 6 | *Gleditsia* | 1,411 | 3.3 | 9 |
| *Tilia* | 961 | 2.9 | 7 | *Prunus* | 1,398 | 3.2 | 5 |
| *Celtis* | 924 | 2.7 | 14 | *Tilia* | 957 | 2.2 | 10 |
| *Pinus* | 742 | 2.2 | 6 | *Picea* | 924 | 2.1 | 10 |
| *Prunus* | 666 | 2.0 | 4 | *Ailanthus* | 872 | 2.0 | 9 |
| *Liquidambar* | 526 | 1.6 | 11 | *Cercis* | 869 | 2.0 | 6 |
| *Ailanthus* | 502 | 1.5 | 11 | *Platanus* | 772 | 1.8 | 9 |
| *Cercis* | 498 | 1.5 | 4 | *Crataegus* | 734 | 1.7 | 4 |
| *Catalpa* | 497 | 1.5 | 18 | *Catalpa* | 701 | 1.6 | 11 |
| *Platanus* | 474 | 1.4 | 18 | *Pinus* | 671 | 1.6 | 11 |
| *Juniperus* | 424 | 1.3 | 5.5 | *Liquidambar* | 655 | 1.5 | 10 |
| *Populus* | 420 | 1.2 | 24 | *Ginkgo* | 586 | 1.4 | 4 |
| 43 others | 2,465 | 7.3 | 6 | 59 others | 6,345 | 14.7 | 5 |
| Total | 33,615 | 100.0 | 9 | Total | 43,169 | 100.0 | 9 |

Spearman's rank correlations revealed significant bivariate correlations between street tree population dynamics and several independent variables (Table 2). Housing unit density most consistently exhibited significant correlations with street tree variables. The relationship was positive with tree density and basal area, and negative with genus diversity (Table 2). Percent of population with bachelor's degree was also positively correlated with all three metrics in 2015, while owner occupancy was negatively correlated with street tree density. Street tree density and genus diversity exhibited stronger and more consistent correlations with socioeconomic variables than did basal area (Table 2). The strongest correlations were observed between present percent of population with a bachelor's degree and tree density ($r_s$ = 0.51), and past basal area and past housing unit density ($r_s$ = 0.47). Significant bivariate relationships between tree density and income (positive) and percent Black or African American (negative) emerged in 2015 (Table 2). Tree density and genus diversity correlations with socioeconomic variables were largely inconsistent with respect to their strength, direction, and significance (Table 2).

**Table 2.** Spearman rank correlation coefficients between tree variables and socioeconomic characteristics

| | Tree density | | Genus diversity | | Basal area | |
|---|---|---|---|---|---|---|
| | **2002** | **2015** | **2002** | **2015** | **2002** | **2015** |
| **Median Household Income** | 0.05 | 0.21** | -0.10 | 0.17* | 0.10 | 0.09 |
| **% with Bachelor Degree** | 0.21** | 0.51** | 0.03 | 0.23** | 0.01 | 0.17* |
| **% Black or African American** | 0.03 | -0.20* | 0.38** | -0.11 | -0.05 | -0.02 |
| **% Owner Occupancy** | -0.37** | -0.17* | -0.03 | 0.06 | -0.03 | 0.08 |
| **Housing Unit Density** | 0.36** | 0.32** | -0.28** | -0.24** | 0.47** | 0.41** |

* $p < 0.05$
** $p < 0.01$

We used SAR models for all of the regression modeling, because each of the OLS models exhibited significant residual spatial autocorrelation. In the multivariate regression models, In the SAR models, insignificant Moran's *I* values indicated the models addressed residual spatial autocorrelation issues present in the OLS models. R-squared values generally decreased between time periods in concurrent models (Table 3). Variation in tree density was better explained by independent variables than genus diversity and basal area. Percent of population with a bachelor's degree was the strongest predictor of tree density in both 2002 and 2015 (Table 3). Housing unit density was positively associated with basal area in both 2002 and 2015. The genus diversity model coefficients are low compared to models for the other two tree metrics, and the model's R-squared value is particularly low (0.13) in 2015.

**Table 3.** Regression coefficients for Concurrent spatial autoregressive (SAR) models

| | Tree density | | Genus diversity | | Basal area | |
|---|---|---|---|---|---|---|
| | **2002** | **2015** | **2002** | **2015** | **2002** | **2015** |
| **Median Household Income** | 0.00* | 0.00 | -0.00 | -0.00 | 0.00 | 0.00 |
| **% with Bachelor Degree** | 0.23** | 0.29** | 0.02 | 0.07** | 0.00 | 0.01 |
| **% Black or African American** | 0.01 | -0.02 | 0.01* | -0.01 | 0.00 | 0.01 |
| **% Owner Occupancy** | -0.03 | 0.06 | -0.01 | 0.00 | 0.01* | 0.02 |
| **Housing Unit Density** | 0.06 | 0.11** | -0.01 | -0.02* | 0.02** | 0.03** |
| **Pseudo R-squared** | 0.57 | 0.42 | 0.32 | 0.13 | 0.40 | 0.30 |

* $p < 0.05$
** $p < 0.01$

The short-term legacy models used 2000 socioeconomic data to explain 2015 tree metrics, and the models yielded less robust results than concurrent models (compare R-squared values in Tables 3 and 4). Past percent of population with a bachelor's degree was positively associated with current tree density and genus diversity. Past housing unit density was negatively associated with current genus diversity, and positively associated with basal area (Table 4).

**Table 4**. Regression coefficients for Legacy spatial autoregressive (SAR) models, based on 2000 socioeconomic data and 2015 tree data

| | **Tree density** | **Genus diversity** | **Basal area** |
|---|---|---|---|
| **Median Household Income** | 0.00 | -0.00 | 0.00 |
| **% with Bachelor Degree** | 0.26** | 0.06** | 0.02 |
| **% Black or African American** | -0.02 | -0.01 | 0.00 |
| **% Owner Occupancy** | -0.04 | -0.00 | 0.02 |
| **Housing Unit Density** | 0.06 | -0.03** | 0.03** |
| **Pseudo R-squared** | 0.37 | 0.11 | 0.28 |

* $p < 0.05$
** $p < 0.01$

The percent change models used 2015 socioeconomic data to explain percent change in tree metrics from 2002 to 2015, and these models also yielded less robust results than concurrent models (compare Tables 3 and 5). Current percent Black or African American was negatively associated with percent change of both tree density and genus diversity (Table 5). Current housing unit density was negatively associated with percent change in tree density, and positively associated with percent change in basal area. Current owner occupancy was positively associated with the percent change of genus diversity (Table 5).

**Table 5**. Regression coefficients for Percent Change spatial autoregressive (SAR) models, based on 2015 socioeconomic data and percent change of tree data from 2002 to 2015

| | **Tree density** | **Genus diversity** | **Basal area** |
|---|---|---|---|
| **Median Household Income** | -0.00 | -0.00 | 0.00 |
| **% with Bachelor Degree** | -0.30 | 0.27 | 0.00 |
| **% Black or African American** | -0.39* | -0.63** | 0.00 |
| **% Owner Occupancy** | -0.21 | 0.62* | 0.01 |
| **Housing Unit Density** | -0.61** | -0.00 | 0.01** |
| **Pseudo R-squared** | 0.25 | 0.23 | 0.14 |

* $p < 0.05$
** $p < 0.01$

## DISCUSSION

The objective of this paper was to examine the relationships among socioeconomic characteristics and a street tree population in the past and present, and to determine how these influences might affect the geography of street tree dynamics over time. We also examined how past socioeconomic characteristics relate to the distribution of the current street tree population. These issues are relevant to cities charged with managing municipal assets such as street trees fairly with respect to heterogeneous socioeconomic patterns across neighborhoods. We expected street tree characteristics to exhibit similar patterns to those found in urban tree canopy; that is, we expected to find lower street tree density and diversity in neighborhoods with lower income and educational attainment and higher percent Black or African American (Danford et al. 2014; Schwarz et al. 2015; Gerrish and Watkins 2018; Watkins and Gerrish 2018). Overall, we found that socioeconomic factors, particularly education and housing unit density, did relate significantly to street tree population characteristics in the past and present. We also found that observed increases in street trees were not distributed equally with respect to socioeconomic factors, and that past socioeconomic factors are associated with observed patterns in the current street tree population.

**Past Street Tree Population**

In both bivariate and multivariate analyses of past data, the percent of the population with a bachelor's degree was a positive predictor of street tree density (Tables 2 and 3). This aligns with a study from Portland, OR in which block groups with lower high school graduation rates were less likely to participate in a street tree planting program (Donovan and Mills 2014), possibly signaling that highly educated residents have a higher demand for street trees or a higher willingness to accept tree plantings in the public right-of-way in front of their houses. Housing unit density was also positively related to street tree density and basal area, and negatively related to genus diversity in the bivariate correlations (Table 2); this could reflect a past aesthetic preference for monoculture street tree plantings along residential streets (Roman et al. 2018). Interestingly, owner occupancy was negatively associated with street tree density in bivariate analysis (Table 2). This contrasts previous studies in which ownership was positively associated with canopy cover (Heynen et al. 2006; Landry and Chakraborty 2009), but note that this correlation was not observed in the multivariate SAR models.

**Present Street Tree Population**

Proactive and coordinated tree planting across Center Township likely led to the observed increases in mean street tree density, mean genus diversity, and mean basal area from 2002 to 2015. The observed increase in street trees contrasts findings of broad urban tree declines across the US (Nowak and Greenfield 2018). The primary factor contributing to this phenomenon was likely successful private and public partnerships focusing on the explicit goal of increasing urban tree canopy in Indianapolis, which resulted in thousands of trees being planted across the city each year (City of Indianapolis DPW staff, personal communication). The increase in street tree densities and total trees (Figures 2 and 3) was somewhat surprising considering the introduction of EAB during the study period. However, it should be noted that *Fraxinus* removals resulting from EAB destruction had not peaked by the 2015 inventory, and the bulk of the county's ash trees remained standing as of the 2015 inventory (Table 1; Bowman 2017). We anticipate accelerated tree losses from 2016 to 2021 as more dead *Fraxinus* trees are removed due to EAB (Bowman 2017), and this will negatively impact basal area because the remaining *Fraxinus* in 2015 had a relatively high median DBH (Table 1).

The increase in the total number of street trees and the reduced importance of the most common genera from 2002 to 2015 (Table 1) help explain increased tree density and increased diversity, respectively. The increased median DBH for genera with steady or declining populations from 2002 to 2015 points to tree growth over time (Table 1), which would translate to higher basal areas. This impact on DBH was reinforced by the net addition of nearly 10,000 trees across Center Township (Table 1), even though it may have taken several newly planted trees to offset basal area lost when one mature tree was removed. A more detailed demographic study tracking individual tree growth, planting, and removal over time could help quantify these effects.

While these gains in tree density, genus diversity, and basal area are encouraging, SAR model results suggest that these increases were not experienced equally. Housing unit density and percent of the population with a bachelor's degree were again significant predictors of street tree density and genus diversity in 2015 (Table 3). Housing unit density was positively related to basal area (Table 3); high density residential areas could see disproportionately high street tree turnover in the coming years as mature trees (especially *Fraxinus*) are removed.

**Legacy Effects**

Socioeconomic and historical legacies have been shown to have an influence on vegetation and tree canopy patterns (Boone et al. 2010; Clarke et al. 2013; Grove et al. 2014; Roman et al. 2018). Our legacy model may not have covered enough time (15 years) to see clear patterns emerge because changes in tree populations and urban socioeconomic characteristics take decades to play out. For example, Boone et al. (2010) showed strong relationships between socioeconomic data in 1960 and vegetation data 40 years later. Although our short-term legacy model explained less variation in all street tree variables than did concurrent models, the model still produced significant associations (Table 4). The positive association between percent of the population with a bachelor's degree and both tree density and genus diversity could reflect higher awareness of tree benefits among highly educated residents (Dawes et al. 2018), which potentially translated to higher demand for tree planting in block groups with higher educational attainment.

**Where Were Trees Planted?**

The most striking evidence of unequal distribution of street trees is seen in percent change model (Table 5). Here, the percent of population that identifies as Black or African American was negatively related to both street tree density and genus diversity (Table 5). This suggests that predominantly Black or African American block groups experienced fewer and less diverse street tree plantings (and possibly higher tree mortality) during the study period. A number of possible explanations could exist for this phenomenon. In Milwaukee, WI urban canopy cover was found to be unequally distributed among race groups included in the study (Heynen et al. 2006). Canopy cover was lower in Hispanic neighborhoods where residents may exhibit different aesthetic preferences, yard maintenance regimes, and less political clout than other parts of the city (Heynen et al. 2006). Differing attitudes towards urban vegetation may also play a role in unequal distributions. Surveys of preferences among Cleveland, OH residents found that Black or African American respondents preferred urban parks with more recreational activities and less natural vegetation and trees (Payne et al. 2002). Similar patterns were found in Baltimore, MD where residents have resisted the city's efforts to afforest predominantly Black or African American neighborhoods due to perceived disamenities associated with trees and concerns about gentrification (Battaglia et al. 2014; Grove et al. 2018). Carmichael and McDonough (2018) describe findings from Detroit, MI where a high number residents refused street tree plantings, in large part because the residents felt excluded from decision making about species selection and responsibilities for tree maintenance. On the other hand, a survey of Alabama urban residents found that race was not associated with differing attitudes towards urban trees and urban forestry programs (Zhang et al. 2007). Qualitative techniques such as interviews could be useful to help understand why the percent Black or African American was negatively associated with changes in tree density and genus diversity in Center Township from 2002 to 2015.

Owner occupancy was also a positive predictor of percent change in genus diversity, indicating that a more diverse set of trees was planted in owner occupied neighborhoods (Table 5). Interestingly, a previous analysis of tree canopy change in Indianapolis did not find that percentage of renters was associated with change in canopy cover (Heynen 2006). This discrepancy may be attributable to differences between both publicly and privately owned trees captured by canopy cover in the Heynen (2006) study vs. only publicly managed street trees considered in this study.

### Limitations

Some limitations to our study deserve mention. We assume census estimates of socioeconomic variables from 2000 and 2015 provide accurate characterizations of conditions in the study area in 2002 and 2015, respectively. With respect to the street tree inventories, we do not have access to quality control data from the contractor, so we cannot assess the reliability of these data sets. It is possible that some trees were included in one inventory but not the other, particularly along streets without planting strips where the extent of the public right-of-way was less clear. It is also possible that some trees were misidentified, but this was likely a very minor issue for our genus level analysis because Ball et al. (2007) observed that most misidentified trees were mistaken for another species in the same genus. Finally, in our analysis we summarized tree metrics at the block group level to match the finest available resolution of census data, so we are unable to provide details of demographic change at the scale of individual trees. For example, we described summarized changes in basal area, but we were not able to explicitly track how new plantings contributed to offsetting the loss of basal area resulting from the removal of a mature tree.

## CONCLUSION

Our results demonstrate an overall increase in street tree density, genus diversity, and basal area between 2002 and 2015 in Center Township. These increases can be explained by ambitious municipal tree planting efforts along with a coordinated campaign by the local nonprofit KIB. While these trends contribute to overall higher access to this public amenity, inequalities that existed in the past persist in the current street tree population. Furthermore, recent tree planting activities appear to be disproportionately focused in neighborhoods with lower percentages of residents who identify as Black or African American.

This study emphasizes the need for managers to consider distributional inequality when writing management plans and executing tree planting projects. The benefits of urban trees are often used as leverage by municipal managers to increase program funding (Silvera Seamans 2013). If benefits to the public are justification for municipal spending, efforts should be made to ensure that the benefits of municipal street trees are experienced equitably among citizens. A clearer understanding of both the supply side (e.g., how urban foresters communicate with residents and implement planting strategies) and the demand side (e.g, tree preferences among residents) is necessary to improve the likelihood that trees are distributed fairly with respect to a city's human population.

To address inequalities in access to street tree benefits, managers need precise information about the street trees they manage. Comprehensive street tree inventories conducted periodically can provide valuable information to monitor changes in the street tree population over time, and to evaluate how street trees are distributed with respect to the socioeconomic characteristics of dynamic human populations. Street tree inventories provide information about individual, municipally managed trees that is difficult or impossible to obtain using tree canopy surveys. This information has clear management utility, for example, to plan for taxonomic diversity and size class diversity within and across neighborhoods. This study is perhaps the first to assess how street tree population dynamics including tree density and genus diversity change over time in relation to underlying socioeconomic factors. As more repeat street tree inventories become available, similar examinations from other cities will help inform more general perspectives on the changing relationships between socioeconomic characteristics and street tree populations over time.

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